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TECHNICAL REPORT
75-5-FSL

RAPID THAWING AND HEATING OF FOODS

by

Malcolm N. Pilsworth Jr.

and

Harold J. Hoge

September 1974

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UNITED STATES ARMY
NATICK LABORATORIES
Natick, Massachusetts 01760

Food Sciences Laboratory

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An apparatus has been designed for the rapid thawing and heating of foods and has been tried out on scalloped potatoes, Creole squash, noodles and cheese, and Spanish rice. Joule heating is used, with the food itself serving as the resistance in which the heat is developed. Power is taken directly from the 60 Hz supply (208 V and up to 20 A) and is transformed as necessary. The foods fall in resistance by a factor of 1000 or more as they are heated. Channeling of the current flow in the food, with consequent uneven heating, can be avoided by making the upper contact to the food in the form of several small electrodes

(4.45 x 4.45 cm), and introducing circuitry to split the total current into smaller, more or less equal currents, one of which flows thru each of the small electrodes. A current-splitting device constructed from modified autotransformers has been developed and successfully applied. Nearly all of the results of the work performed so far are highly encouraging. Problems still to be solved are discussed.

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FOREWORD

The Food Engineering Laboratory (FEL) is the Lead Laboratory for a Work Unit titled "Rapid Thawing and Heating of Bulk Packaged Prepared Frozen Foods." This Unit is U.S. Air Force Requirement 5–1. Discussions took place between representatives of FEL and the Food Science Laboratory (FSL) which led to the work described in the present report. At the time the work was undertaken the FEL and FSL had not been established; the individuals involved were then members of the General Equipment and Packaging Laboratory (GEPL) and of the Pioneering Research Laboratory (PRL). The present report does not cover all of the work that is now under way or contemplated which is directed toward USAF Requirement 5–1. It deals only with the work done by FSL (formerly PRL). Other work is being carried out by others under the auspices of FEL (formerly GEPL).

The present report is a progress report. The USAF Requirement 5–1 has not yet been met, but substantial progress toward meeting it has been made. The efforts of FEL and FSL should both be continued until the problem has been satisfactorily solved.

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ABSTRACT

An apparatus has been designed for the rapid thawing and heating of foods and has been tried out on scalloped potatoes, Creole squash, noodles and cheese, and Spanish rice. Joule heating is used, with the food itself serving as the resistance in which the heat is developed. Power is taken directly from the 60 Hz supply (208 V and up to 20 A) and is transformed as necessary. The foods fall in resistance by a factor of 1000 or more as they are heated. Channeling of the current flow in the food, with consequent uneven heating, can be avoided by making the upper contact to the food in the form of several small electrodes (4.45 x 4.45 cm), and introducing circuitry to split the total current into smaller, more or less equal currents, one of which flows thru each of the small electrodes. A current-splitting device constructed from modified auto-transformers has been developed and successfully applied. Nearly all of the results of the work performed so far are highly encouraging. Problems still to be solved are discussed.

1. Introduction

In August 1973 the authors undertook a study of the rapid thawing and heating of foods, using the food itself as the resistance element and passing ordinary 60 Hz current thru the food between electrodes in direct contact with the food. Air Force Requirement 5–1 calls for the heating of a steam-table pan of frozen prepared food from –23C (–10F) to serving temperature in a period of 20 minutes. This is approximately 1/3 the time that would be required to thaw and heat the food in an oven containing a fan to circulate the air, and approximately 1/4 the time that would be required in a conventional oven. The lead Laboratory for work on this Air Force Requirement is the Food Engineering Laboratory (FEL) and the project leader is R. V. Decareau.

In addition to the direct ohmic (Joule) heating to be decribed in the present report, microwave heating, infrared heating, and steam heating are being studied or considered by FEL and by the Food Science Laboratory (FSL) as ways of meeting the AF requirement. It may well be that a combination of methods will furnish a more convenient and practical solution to the problem of rapid heating than any one method used alone.

The present work in which the food itself carries current between contacting electrodes has now progressed to a point where the major difficulties have probably all been encountered. Heating times approaching the specified 20 minutes have been achieved. A number of experimental arrangements, particularly regarding the construction of the electrodes and the design of circuits for the uniform distribution of heating current, have been tried out. The work is now at an appropriate stage for the writing of a progress report. The present report will summarize our results to date. It will not necessarily be chronological, but will begin with a description of the best methods and techniques developed to date. This will be followed with typical experimental data. Then, as a help to others who may be planning experiments, brief descriptions of some of our earlier, often less successful experiments will be given.

Uniform distribution of heat thruout the food is the most important problem encountered in ohmic heating. If both the top and the bottom electrodes are single plates, channeling of the flow of electric current is likely to occur. The channeling becomes serious when the thickness of the food is much less than its other dimension or dimensions. For example, a cube of food of edge a heated by current flowing between two opposite faces might not show serious channeling; however, a slab of dimensions a x a x a/3, with current flowing in the direction of the short dimension, would probably show serious channeling. Channeling of current is of course to be expected in food, since the electrical resistance decreases as the temperature rises. If from any cause a small part of the cross section of the food becomes warmer than surrounding parts, it will tend to rob its surroundings of their normal share of the current. This will aggravate the situation by further heating the warm region and further reducing its resistance. The problem can be controlled by making the upper electrode not as a single plate but as a set of electrically separate sections, each constrained to carry approximately its proper share of the total current.

After the problem of channeling, the next most important problem is that of making good electrical contact with the food. The frozen food may have uneven surfaces, especially on the top, and a flat electrode cannot be depended upon to make good contact. A flat electrode generally serves all right at the bottom of a specimen, and electrodes having fairly sharp points generally make good contact at the top. However, electrodes with sharp points are a nuisance to handle and to clean.

A problem that will require some ingenuity is how to maintain the power input at a high, near-constant level while the resistance of the food is changing by a factor of 1000 or even more. This high power-level will probably be near the maximum that can be drawn from the power line, unless special lines are installed.

Other problems that have to be considered in ohmic heating are the avoidance of surface burning, the effect of the electrodes on surface appearance, and the avoidance of damage to food or equipment if a direct short occurs between the top and bottom electrodes. If the electrodes come close to the sides of the pan, channeling is invited. On the other hand, if they are too far from the edge there may be a region that receives insufficient heat. As always when electricity is used there are problems of operator safety that must be considered. The stainless steel pans seem to discolor more rapidly when they serve as the lower electrode than when no current flows thru them. In addition to discoloration it is possible that some etching of the metal occurs.

2. Apparatus

The equipment and methods now in use have been developed in a series of experiments extending over more than nine months. As problems became apparent, apparatus and techniques were modified to solve them. The process is not yet complete but we are now able to heat foods much faster than they can be heated in conventional ovens.

All of the experiments made to date have been performed on smaller quantities of food than is contained in a full steam-table pan. This has reduced the cost of food and equipment, but more important, it has greatly reduced the work of setting up equipment, and of handling, preparing, and storing the food. It has also simplified the problem of getting adequate power from the 60 Hz supply. The amount of food normally heated in a run is about 1/5 as much as would fill a standard-size steam-table pan. The thickness of the food specimen used is however approximately the same as it would be in a standard pan and hence the heating times are expected to be the same as they would be in full-size steam-table pans. The equipment now in use is shown schematically in Figure 1. The food sits on a lower electrode, which is normally the bottom of a steam-table pan. The food is held in place by bakelite retaining walls that keep it from spreading after it melts. These walls are used for convenience in performing the experimental work and it is not anticipated that they would be used in routine, dining-hall food preparation.

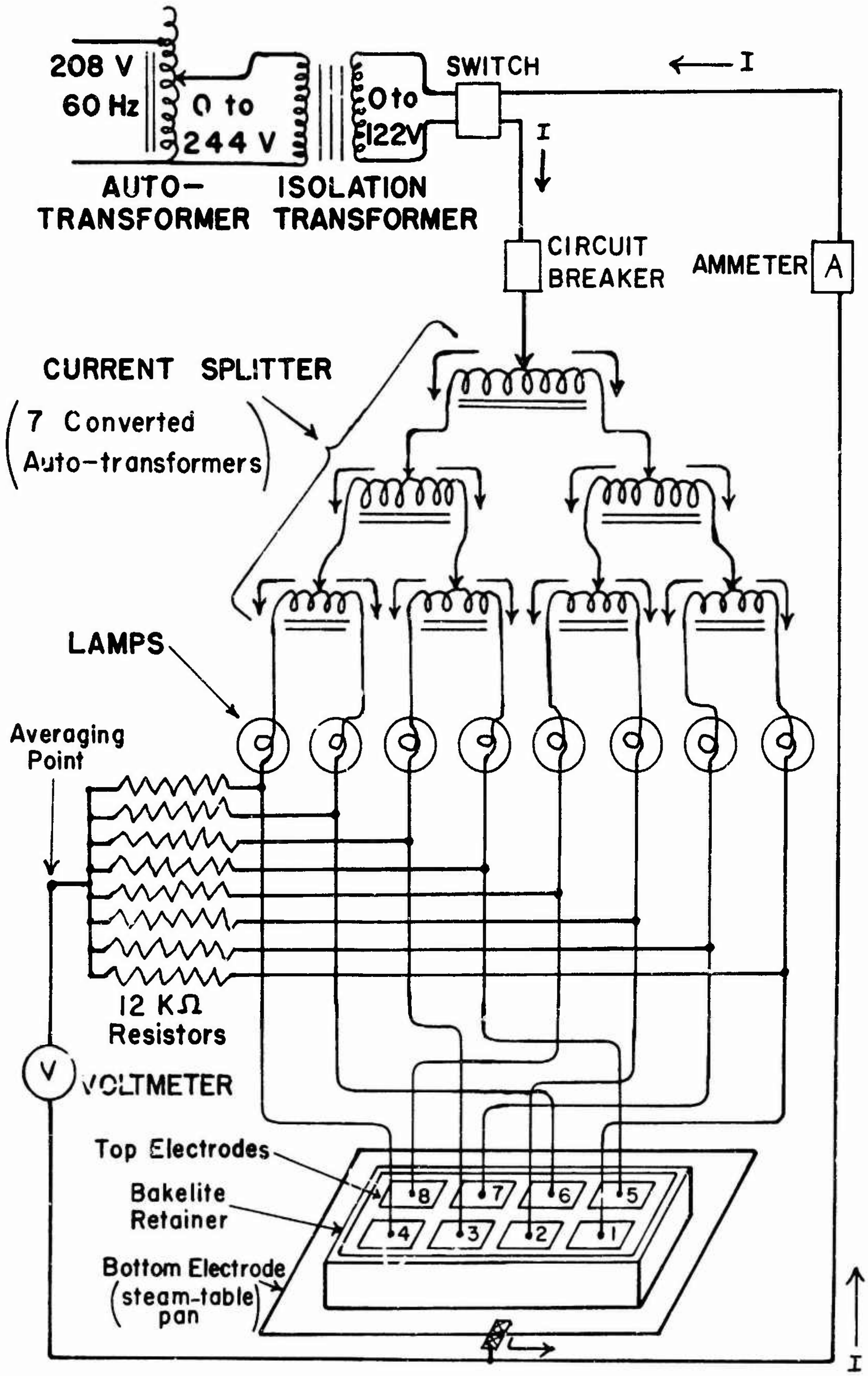

Figure 1. Schematic diagram of apparatus now in use for rapid heating. Food is placed inside retainer, between top and bottom electrodes.

The upper electrode assembly, shown in Figure 2, consists of 8 small electrodes. Each electrode is backed by a coil spring. The electrodes and springs are held in place by a bakelite backing plate that permits force to be applied from above when needed to improve the electrical contact between electrodes and food. The 8 small electrodes are all fed from the same source, but a "current-splitter", to be described later, causes the currents flowing thru the various electrodes to remain roughly equal, even when the food resistances below the different electrodes are unequal.

The electrode assembly fits over a food specimen of area 22.9 x 11.4 cm (9 x 4.5 inches). Each electrode is 4.45 x 4.45 cm (1.75 x 1.75 inches); the distance between adjacent electrodes is 1.27 cm (0.5 inch) and the food extends 0.64 cm (0.25 inch) beyond the electrodes at the outer edges.

The under side of the electrode assembly is shown in Figure 2. There are 16 dark spots on each of the small electrodes; each dark spot is a cylindrical insert with a projecting conical point. When the assembly is set on top of a food specimen and a downward force is applied to it, the points penetrate into the food and make much better electrical contact than can be obtained with flat electrodes.

The device for exerting force on the electrode assembly may be seen in Figure 3. The food and the electrodes are placed inside a transparent protective box with open ends. A converted drill press is mounted on top of this box. The press carries a bakelite rod that passes thru a hole in the top of the box. By pulling down on the handle of the press, force is exerted on the top electrode-assembly. A force of about 85 pounds was normally applied to the assembly; this is about 2 psi on the food surface.

The protective box has inside dimensions of 82 x 38 x 20 cm (32 x 15 x 8 inches). It is made of 1.27 cm (0.5 inch) polycarbonate, which is stronger than polystyrene or poly(methylmethacrylate). The open ends of the box allow the food to be slid into place easily and yet offer some electrical protection to the operator. Voltages up to about 250 V have been applied across the food in some of our experiments.

One or more thermocouples are inserted in the food. Usually only one was used, and was placed at the center or slightly below the center of the block of food. Sometimes a couple was placed directly below one of the 8 upper electrodes, and sometimes other locations were used. The emf of the thermocouple (or of the main thermocouple) is normally fed to a General Radio Model 1807 dc amplifier and null detector. This amplifier indicates the output in millivolts and also drives a recorder where the output is recorded on a 10–inch strip chart.

The thermocouples are in electrical contact with the food and are often influenced by electrical pickup when the heating current is flowing. This pickup is reduced but

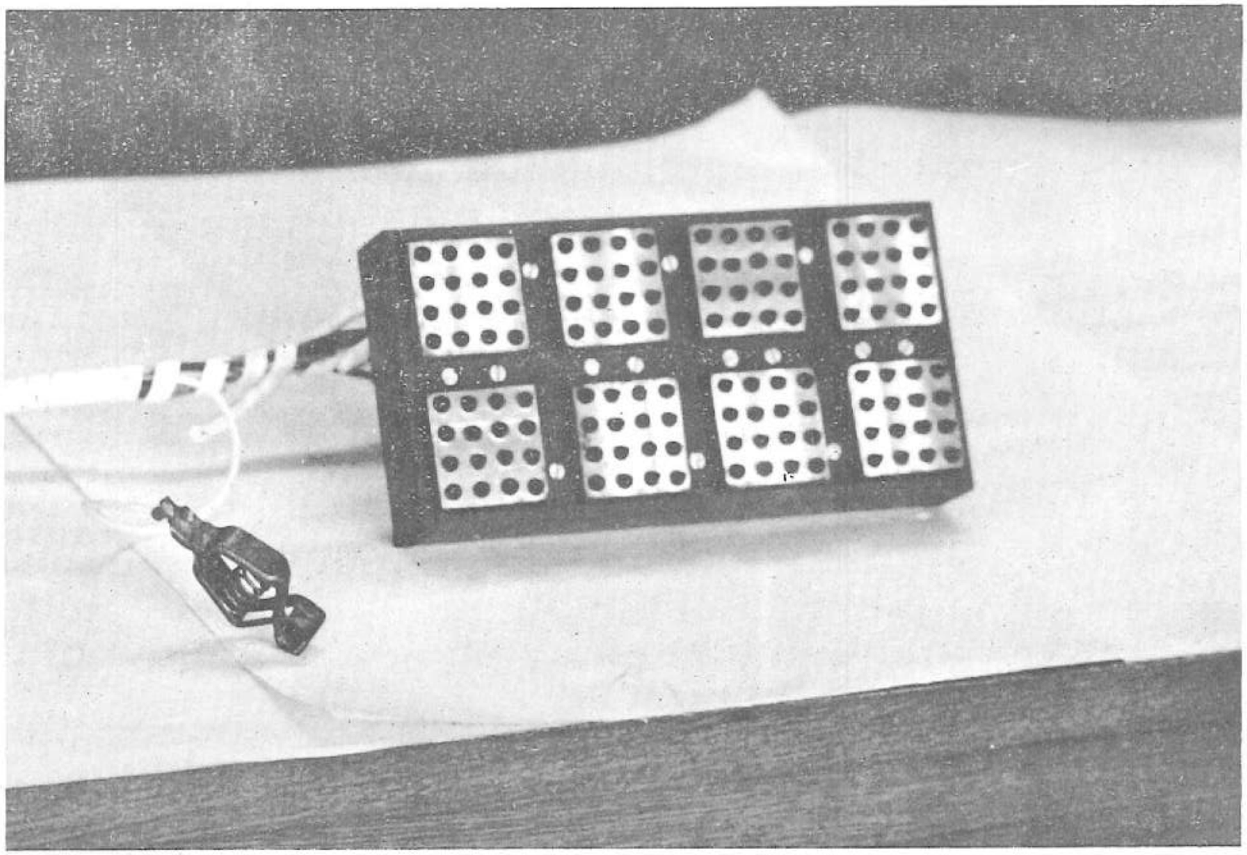

Figure 2. Photo of upper electrode assembly. Each of the 8 metal plates carries 16 sharp spikes that penetrate into the food and make good electrical contact with it.

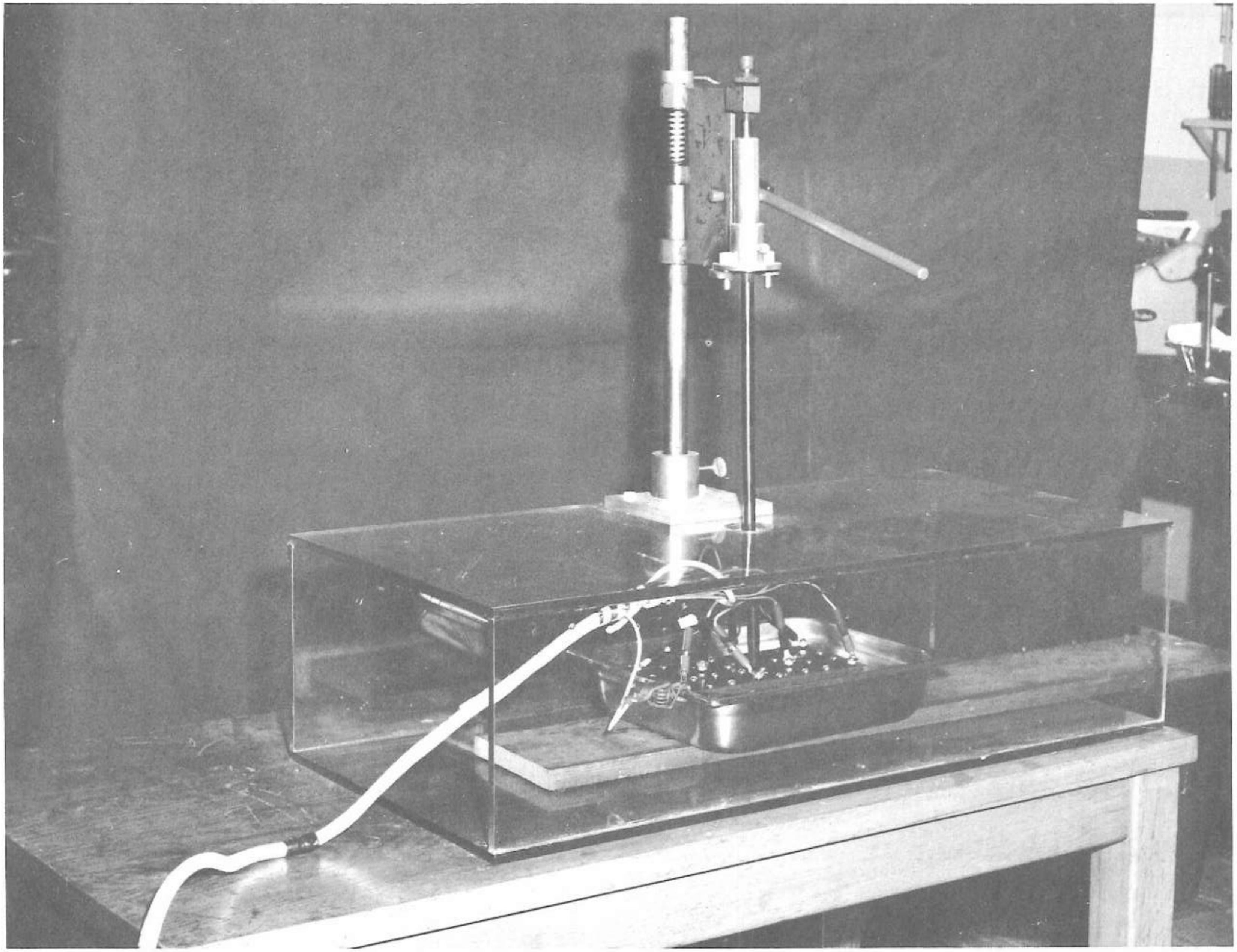

Figure 3. Protective box with electrodes and pan inside it. A press mounted on top of the box permits a downward force to be applied to the upper electrode assembly, to improve electrical contact.

not eliminated by the use of isolation transformers in the power-supply lines of the dc amplifier and the recorder. It could be further reduced by coating the thermocouples with insulating varnish. It is believed that temperatures indicated by the thermocouples were generally not more than a few degrees in error because of electrical pickup.

Power for the heating is taken from a 208 V, 60 Hz supply line. A 230 V supply would have given slightly higher heating rates but was not available. The power is supplied to an autotransformer (9A) which delivers any desired voltage from 0 to 244 V. The output from the autotransformer is fed to an isolation transformer (3KVA) where the voltage is stepped down by a factor of 2. This permits a current of up to 18 amperes to be passed thru the food without overloading the 9-ampere autotransformer. A 1-to-1 connection of the isolation transformer could be used; it would give more rapid heating near the beginning of an experiment but would give slower heating near the end.

The need for a current splitter, to divide the total heating current into 8 approximately equal currents, was mentioned earlier. The simplest and most obvious current splitter would be a set of 8 large impedances, each in series with one of the upper electrode sections, and all fed by the line that passes thru the circuit breaker. However, large impedances will have large voltage drops across them. If they are resistors, they will waste large amounts of power. If they are capacitors they must be paper or other relatively expensive types (electrolytic capacitors will overheat and explode). Inductors are probably the best choice for impedance, but they also will be large and fairly expensive.

If adequate current-splitting is to be performed by the use of parallel impedances, the relatively large voltage drops across them are a serious disadvantage. This caused us to consider systems in which the major part of the current splitting is accomplished by transformer action. Out of these investigations the current splitter shown in Figure 1 evolved.

The current splitter consists of 7 autotransformers connected in a pyramidal arrangement as shown in the figure. All of the heating current flows into the pyramid thru the brush of the top transformer. At the brush, the current ideally splits into two equal parts, so that half the current flows toward one end of the winding and the other half toward the other end. The two currents emerge at the two points where, in ordinary use, line voltage is connected to the winding. The brush is set at a point midway between these taps. The directions of flow of the two currents are such that their core-fluxes tend to cancel, and if the currents are equal there will be almost no flux in the transformer core and almost no voltage drop across it, from brush to either tap. However, if the two currents are not equal a net flux will be present, accompanied by voltages that reduce the larger current and increase the smaller current.

The first splitting is done by a 20A Variac, which is located at the top of the pyramid. The second splitting is done by two 10A Variacs, which are located just below the first Variac. The third splitting is done by four 7A Powerstats, which are located at the base of the pyramid. Each autotransformer receives current thru its brush and splits it into two more or less equal currents that flow onward toward the food. At the bottom of the current-splitter, 8 currents emerge and flow to the 8 lamps shown immediately below the pyramid. From the lamps they flow to the 8 electrodes and thru the food to the common return line.

When the total current is 18 amperes, each branch carries over 2 amperes, and each of the "lamps" shown in Figure 1 actually consists of a 150 and a 200 watt lamp in parallel. The lamps are included partly because of their equalizing effect on the currents, partly as a protection in case of shorts, and partly because their brightness is a convenient indication of the degree of equality among the 8 separate currents.

The use of lamps in series with the electrode sections would of course be undersirable in any practical device for routine rapid heating; more power is wasted in the lamps than is developed in the food. We have made some auxiliary measurements on smoothing filter reactors such as are used in the power supplies of electronic equipment, and it appears that suitable reactors could be used to replace the lamps shown in Figure 1. The Triad C–56 U, rated at 0.035 henry when carrying 2 amperes dc appears to be about the right size, using one reactor in series with each of our 8 electrodes. The reactor has an impedance of 20 to 25 ohms at 60 Hz when the load is entirely ac. Its dc resistance is only 0.75 ohm and so there would be very little power wasted if the reactors were used instead of lamps. A set of these reactors has now been obtained. If they work as expected, a further improvement would be to obtain them with somewhat heavier windings so that currents of 3 to 4 amperes could be passed thru them.

The voltage drops observed from the 8 top electrodes to the bottom electrode varied somewhat because of differences in food resistance. In order to compute the power supplied to the food, an average value of the voltage across the food is needed. This is obtained by connecting each electrode section to a common averaging point thru a 12,000-ohm resistor, as shown in Figure 1, and measuring the voltage between the averaging point and the bottom electrode. The voltage drops for individual electrodes are measured between the bottom electrode and contact points placed at ends of the averaging resistors not connected to the averaging point.

Voltage drops across the food and the total current thru it are measured with a Keithley Model 165 digital multimeter or with a Hewlett-Packard Model 400–D ac voltmeter. Overall voltages (food + splitter and lamps) are measured with a conventional multimeter.

The current splitters have a strong tendency to split the current they receive into equal parts, and in situations where one of the upper electrode sections makes very poor contact with the food, the voltage between it and the lower electrode may be much higher than the average voltage across the food. Sparking and electrical breakdown may then occur between the electrode that has a high voltage and one of its neighbors. This can damage the upper electrode assembly, burning holes in the bakelite supports and roughening the electrodes. It can also result in burned food. The sparking generally makes a loud noise and is usually accompanied by sudden changes in brightness of the lamps that are in series with the electrodes. Electrical breakdown seems to occur mainly when the upper electrodes have no sharp points to penetrate the food, but it is potentially present in any experiment.

If one electrode makes very poor contact, the current-splitter will increase the voltage applied to it. This requires that the electrode with which it is paired receive a reduced voltage. It is therefore desirable that electrodes not be paired with either of their closest neighbors. The pairing arrangement adopted is shown in Figure 1. Chess players will recognize that a knight could legally be moved from any electrode to the electrode with which it is paired.

Proper pairing of electrodes is often not enough to prevent electrical breakdown. We therefore tried the expedient of partially defeating the current-equalizing action of the current-splitter. The most convenient method found for doing this was to replace the averaging resistors in Figure 1 by lower-value resistors that would produce a significant redistribution of current from high-voltage electrodes to lower-voltage electrodes; 25-watt lamps served satisfactorily as redistributing resistors.

It occurred to us that we might avoid unduly high voltages and electrical breakdown more elegantly by simply using fewer turns of each autotransformer in the current splitter. However, this scheme requires further experiments before it is adopted. For one thing, current splitting does not seem to be very effective when the currents (or their differences) are smaller than the magnetizing current of the transformer. If the number of turns on a current-splitting transformer is reduced, we may get poor current-equalization quite early in a run when the total current is small.

3. Procedures

The foods used were prepared by the Food Laboratory (mostly by R. L. Helmer) and were received in disposable aluminum pans. A rectangular block (22.9 x 11.4 x 5.1 cm) of the frozen food was sawed out and drilled for the insertion of one or more thermocouples, using a No. 60 extension drill. The bottom surface of the food was usually smooth, but the upper surface was often irregular or rough. In the case of large irregularities the upper surface of the food was smoothed with a file or rasp.

After thermocouples had been inserted, the food was placed inside the bakelite retainer and put under refrigeration (usually overnight) at −10 to −15C. When a run was to be made, the food, retainer and thermocouples were removed from refrigeration and placed in the pan that served as the lower electrode. The upper electrode assembly was set on the food, the electrical connections were made, and the entire assembly was slid into the protective box. Force was applied to the upper electrodes by means of the lever and a weight was hung on the lever, to remain until the food softened. The power was turned on, the stopclock was started, and the voltage was raised to its maximum value of about 122 V in less than a minute. If all went well, this voltage was not lowered until the run was nearly over. Near the end of the run the heating current often reached 18 amperes, and when this value was reached the voltage was gradually lowered to keep the current at this maximum value. This was done to protect the electrical equipment and not on account of the food. If poor contact was experienced, it was generally necessary to lower or turn off the voltage and increase or redistribute the pressure between the upper electrodes and the food.

The current was quite small at first, but with 122 V across splitter, lamps, and food it usually reached 1 ampere after 3 to 9 minutes depending strongly on the initial temperature of the food. This time would of course be increased if the food were initially at −23C as specified in USAF Requirement 5–1. No convenient refrigerator was available in the laboratory to hold the food at the lower temperature. Melting of the ice was generally complete after 6 to 13 minutes and the food reached 75C after 12 to 30 minutes. Readings of total voltage, voltage across the food, and total current were made at regular intervals. These data and the strip-chart record permitted graphs of temperature, power, and other quantities to be plotted as functions of time.

As soon as heating was stopped, the food was normally removed from the protective box, the upper-electrode assembly was lifted off, and the food was explored with a mercury thermometer or a thermocouple to see how uniformly the heat had been distributed. This normally completed a run.

In some cases the food was refrozen after a run and used again later. In other cases it was discarded. Food such as Creole squash that loses a great deal of liquid when heated is generally not suitable for re-use.

Exploration of the food often showed substantial non-uniformity of temperature. This shows that the recorded temperature (thermocouple emf) may correspond to either a hot region or a cold region and may therefore not be equal to the average temperature in the food. This situation has led us to construct a stirred-water calorimeter with which enthalpy changes can be measured. If the enthalpy content of a food is known as a function of temperature, and if a specimen of non-uniform temperature is measured in the calorimeter, its average temperature can be computed from its measured enthalpy. Only a few enthalpy measurements have been made so far, but the accuracy appears to

be adequate for present purposes. The calorimeter will permit us to obtain specific-heat data from the measured enthalpies and will allow us to compute how much of the energy supplied to the food is retained and how much is lost to the surroundings. There are of course specific-heat and enthalpy data for a number of foods in the literature, but it is desirable to have measured values for the foods actually used in the rapid heating experiments, because the specific heat of food depends strongly on its water content.

4. Main Results

Rapid thawing and heating experiments have so far been performed on five foods: noodles and cheese, scalloped potatoes, Creole squash, Spanish rice, and raw beef. Table 1 contains data on all the runs that have been made on full-size (22.9 x 11.4 cm, 9 x 4.5 inch) specimens. All the experiments on beef and most of those on scalloped potatoes were made on much smaller specimens (areas about 4.8 x 3.5 cm) and served mainly to show that ohmic heating was possible.

The Creole squash and scalloped potatoes were used simply because they had already been prepared and were available. The scalloped potatoes yielded useful data but the Creole squash lost so much water during heating that its thickness decreased by about half. The loss could be prevented, of course, if the squash completely filled the containing vessel. More runs have been made so far on noodles and cheese than on any of the other foods. The food heats well but sometimes exhibits non-uniform temperatures. At this writing only one run has been made on Spanish rice. The rice was made with a thickened sauce to reduce fluid loss but even so a substantial amount of rather clear liquid runs out of the food as it is heated.

Figure 4a shows Run 18, which is one of the better runs on noodles and cheese. Power input and the temperature indicated by the thermocouple are plotted against time. The power was turned on (120 V across the food) at time t = 0. It was turned off for a period of about 1 minute at approximately t = 16.5 minutes and then remained on until the end of the run at t = 24 minutes. The actual heating time was 23 minutes, the total energy input was 460,200 joules (0.128 kWh) and the average power input was 333 watts. According to the thermocouple the specimen was heated from −15.3C (+4.5 F) to 96C (205 F). The specimen was not weighed, but by comparison with similar specimens it was estimated to weigh about 920 g (2.03 lb.). A full-sized pan should heat in the same length of time. The voltage required would be the same. The current required would be roughly 5 times that required in our experiment, and the total energy required for heating would also be 5 times greater.

Figure 4b shows results for Run 20, in which the food was Spanish rice. The specimen weighed 970 g (2.14 lb.), slightly more than the noodles and cheese, and required 31 minutes to heat compared to 23 minutes for the noodles and cheese. The total energy

Table 1. Summary of experimental data for Runs 1-20. Also, data on the foods employed, the top electrode used, and the storage temperature.

FOOD	SYMBOL	%H_2O	Typical Wt. grams
Scalloped Potatoes	SP	81.6	1640
Creole Squash	CS	-	983
Noodles and Cheese	NC	66.8	922
Spanish Rice	SR	77.3	970

RUNS	TOP ELECTRODE
1-3	Single plate
4-10	8 Flat plates
11	1-Spike plates
12-20	16-Spike plates

RUNS	STORAGE TEMPERATURE
1-17	-11 C
18-20	-16 C

Run	Food	Max E_t	Max I	Max Power	Energy to Food	Heating Time	Max T Recorded	Temperature Distribution
		volts	amps	watts	K Whr	min	C	
1	SP	250	9.0	1380	0.139	14	90	Very poor
2	SP	250	9.0	1388	-	14	-	Very poor
3	CS	210	9.0	372	.102	30	52	Poor
4	CS	139	9.0	-	-	92	38	Good
5	CS	130	10.0	-	-	43.5	55	Fair
6	CS	136	11.0	-	-	55.5	50	Fair to Poor
7	CS	116	12.0	-	-	40	54	Fair
8	NC	225	8.1	-	-	70.2	55	Fair to Poor
9	NC	165	10.0	-	-	32	65	Fair to Poor
10	NC	175	12.0	-	-	33	57	Fair
11	NC	125	10.0	-	-	40	- 2	Very Poor
12	NC	155	11.0	-	-	48	69	Fair
13	NC	217	12.0	525	.123	35	52	Fair
14	NC	120	16.8	811	-	11	- 1.5	(Fuse failed)
15	NC	123	16.0	921	.139	24	88	Fair
16	NC	120	18.0	756	.117	15	73	Poor
17	NC	120	18.0	812	.116	15	100	Fair
18	NC	120	18.1	850	.128	23	96	Fair
19	NC	122	18.0	415	.131	40	88	Poor
20	SR	124	18.0	772	.174	31	85	Very good

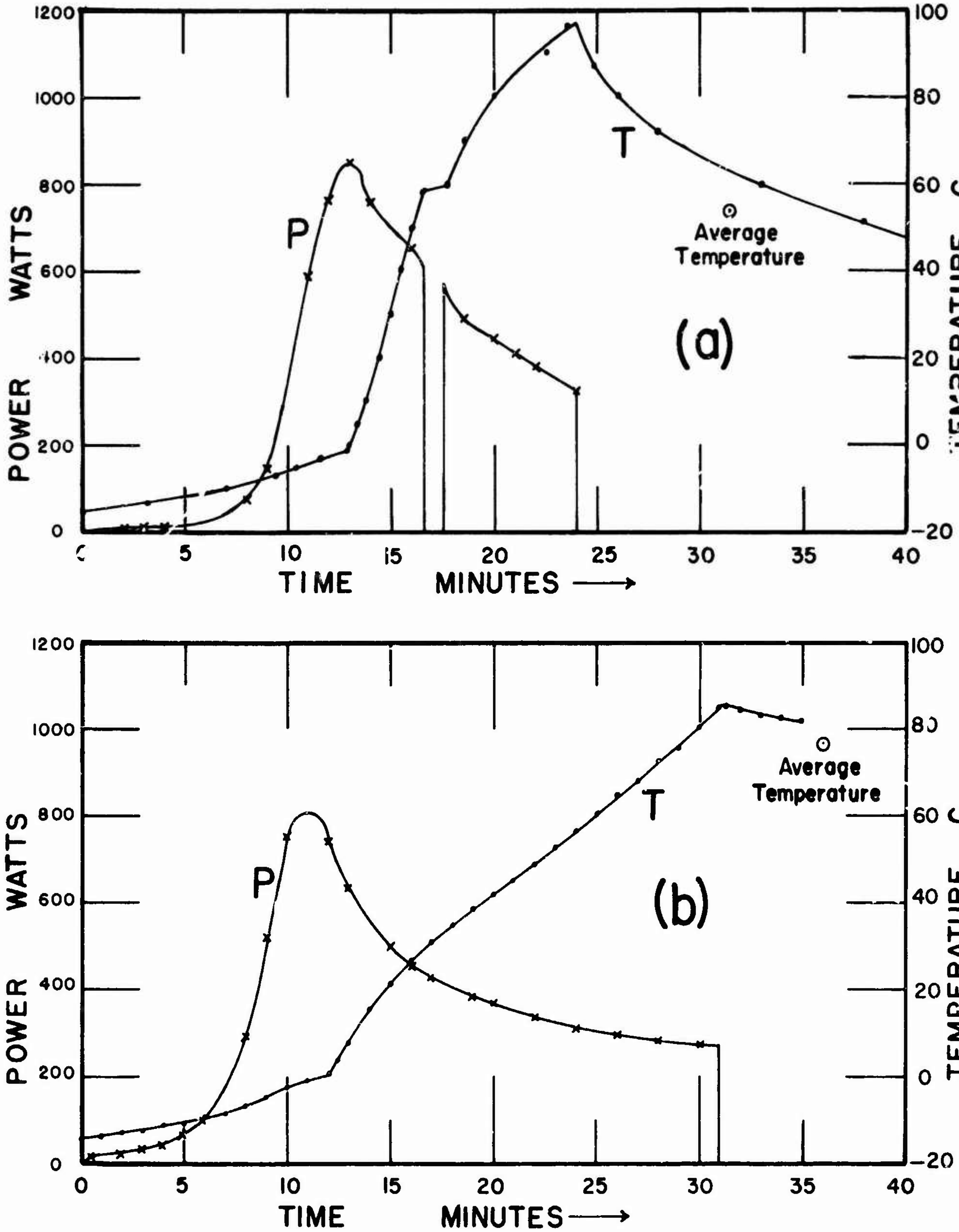

Figure 4. a. Run 18, noodles and cheese. Power (P) developed in the food, and temperature (T) indicated by a thermocouple imbeded in the food, as functions of time. b. Run 20, Spanish rice. The same quantities are shown as in part a.

supplied to the Spanish rice was 626,000 joules (0.174 kWh) and the average power input was 337 watts. The temperature rose from −14.5C (5.9 F) to 85C (185 F). The slow heating of the Spanish rice is mainly due to its high heat capacity. Since water has a high specific heat, the heat capacity of a food is strongly dependent on its water content. Table 1 contains the percentages of water in three of the foods investigated, as determined by freeze-drying. The noodles and cheese contained 66.8% water, whereas the Spanish rice contained 77.3%. This difference helps to account for the observed difference in heating times.

A minor difference between Run 18 and Run 20 was the use of 25W lamps (in place of the 12K resistors of Figure 1) in Run 18. These lamps partially defeat the current splitting performed by the autotransformers and reduce the tendency to sparking and arcing. Since the electrodes with sharp points were also very effective in preventing arcing, it was decided to remove the lamps before Run 20, using the 12K resistors for voltage averaging only, since their resistances were too high to have much effect on the current distribution. No electrical breakdown was observed during Run 20.

The very large resistance change of foods during thawing and heating is shown in Figure 5. Here R is plotted versus temperature for the two runs just discussed and for Run 15, an earlier run on noodles and cheese. Note that the resistance scale is logarithmic and the resistances range from below 1 ohm to above 1000 ohms. In the frozen state the resistance falls very rapidly as the temperature rises. Then in the melting region there is a break in the curve, followed by a much slower fall in R as T rises further.

The shape of the R vs T curves raised the question of whether the electrical conductivity of the foods could be explained in terms of two different activation energies, one for some process occurring in the frozen food and the other for some process occurring after melting took place. When an activation energy is involved, the electrical conductance should obey $\sigma = \sigma_0 \exp(-\epsilon/kT)$ where ϵ is the activation energy. Since conductance is 1/R we may replace σ by 1/R. Then, taking logarithms

$$-\ell n\ R = -\ell n\ R_0 - \frac{\epsilon}{k}\left(\frac{1}{T}\right)$$

Changing signs, we see that if ℓn R is plotted versus 1/T, a straight line of slope ϵ/k should be obtained. Figure 6 shows such a graph for Run 15 (noodles and cheese). No special effort was made to get accurate values of food resistance. Measurements of E and I were simply made "on the run" and R was calculated from them. By allowing the temperature to equilibrate after a heating period, more accurate values of R could undoubtedly be obtained.

The "frozen" and "non-frozen" branches of the curve in Figure 6 are surprisingly-well represented by straight lines. The calculated activation energy in the frozen state is 4.18 electron volts and in the non-frozen state, 0.050 eV. A graph (not shown) similar to

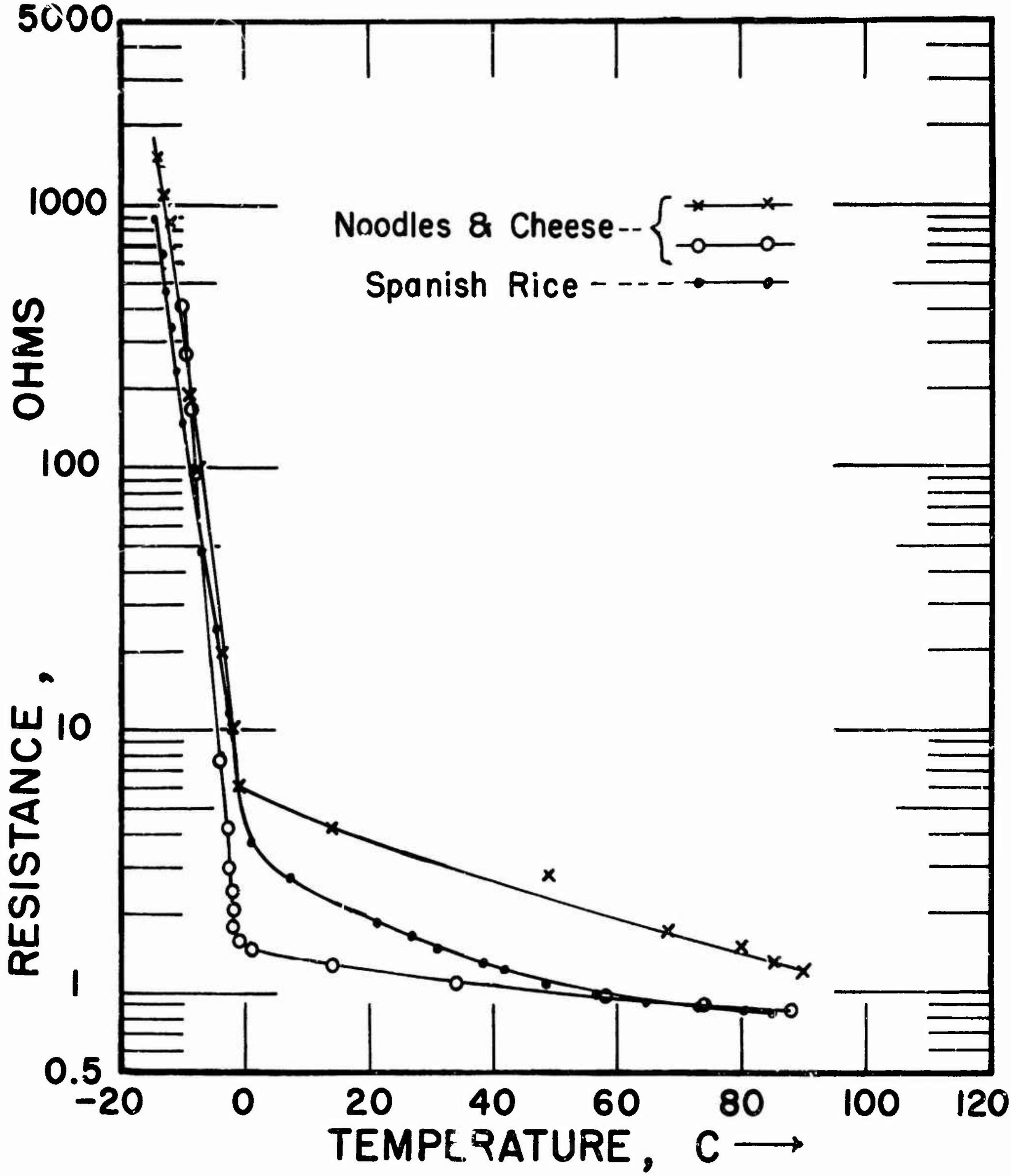

Figure 5. Resistances of 3 different food specimens as a function of temperature.

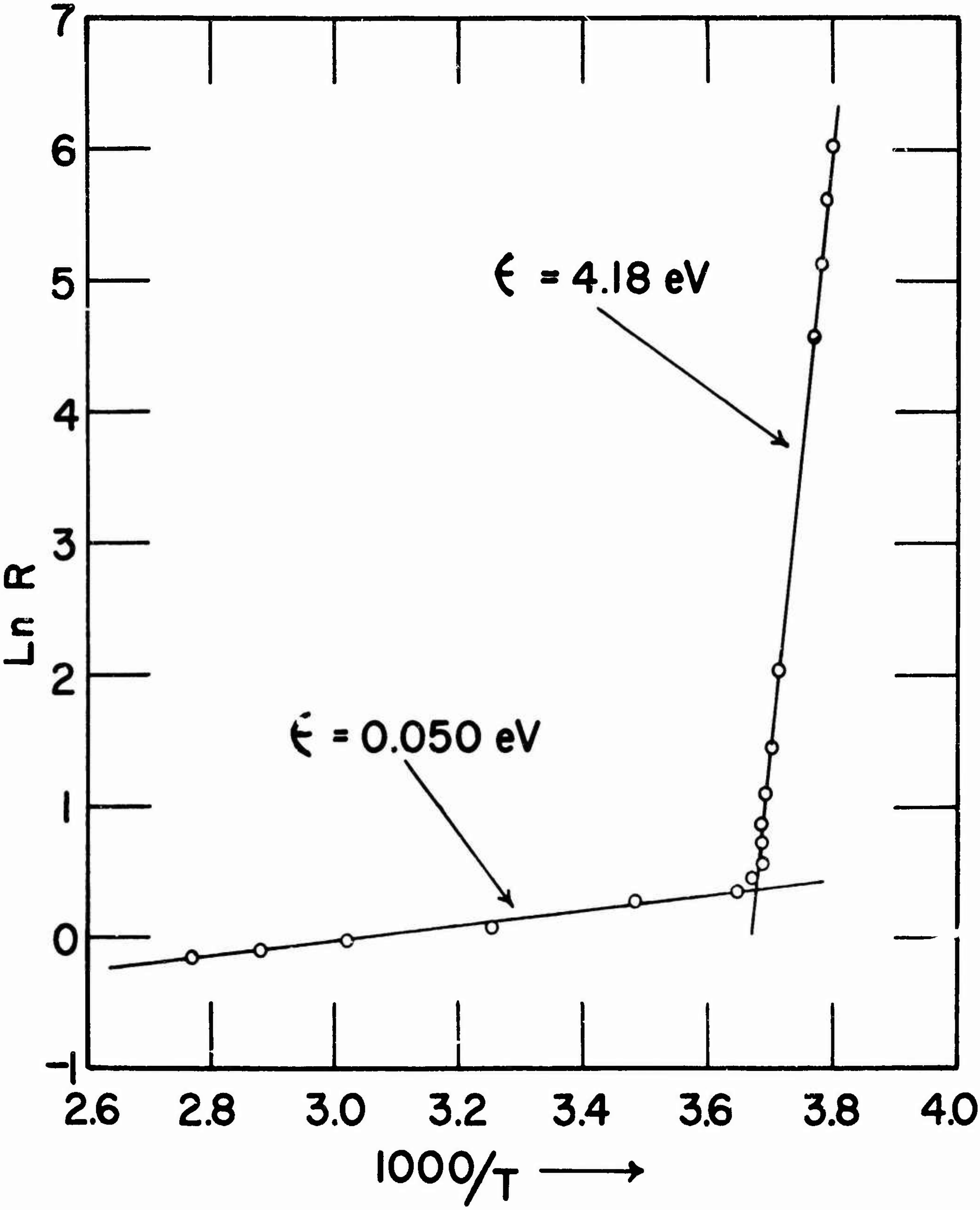

Figure 6. Graph plotted from the resistance data of Run 15 (noodles and cheese). A graph of this type gives the activation energies (ϵ) that characterize the food. Note that the frozen food has a very much higher activation energy (4.18 eV) than the non-frozen food (0.050 eV).

Figure 6 was drawn for Run 20 (Spanish rice). Again a good straight line was found for the frozen region, but the line for the non-frozen region was curved. The activation energy for the frozen state was 2.25eV. It is possible that in the non-frozen region of Run 20 the temperature was not as uniform as it was in Run 15. We will not attempt an explanation of the mechanism or mechanisms that may be responsible for these activation energies. The values found for the frozen region (4.18 and 2.25eV) are rather high. The two well-defined straight lines in Figure 6 are an indication of two distinct, well-defined phases. This may be in conflict with the widely-held view that a frozen food contains a substantial proportion of liquid phase, which persists for many degrees below the temperature where the bulk of the food is frozen.

Because of the large changes in resistance, our runs always began with relatively high voltages and low currents and ended with low voltages and high currents. Figure 7 shows the actual values of E and I for the food during Run 20. The values shown in this figure are not the optimum for rapid heating; they are simply an approach to the optimum that was serverely limited by the voltage and current ranges of our equipment.

Each of the temperature curves of Figure 4 was obtained from a strip-chart record of thermocouple emf. In Run 18 the thermocouple was directly under electrode 3 (see Figure 1 for the locations of the various electrodes). A couple directly under an electrode can be expected to reach a temperature somewhat higher than the average of the entire food specimen, because the electrodes are separated from each other by 1.27 cm (0.5 inch) distances, and so a part of the food will carry less current than the regions in direct contact with electrodes. When the temperatures were explored after the termination of heating in Run 18, the following values were observed directly below the electrodes: electrode 1, 62C; 2, 73C; 3, 67C; 4, 60C; 5, 49C; 6, 53C; 7, 67C; 8, 51C; average 60C. In addition, measurements were made at the 4 corners of the specimen, just outside the electrodes and just inside the food boundary. At the corner nearest to electrode 1 the temperature was 63C; nearest 4, 63C; nearest 5, 43C; nearest 8, 15C; average 46C. Equidistant from the adjacent corners of electrodes 1, 2, 5 and 6 the temperature was 32C; equidistant from 3, 4, 7, and 8 the temperature was 53C; average 42C.

The temperature distribution found after Run 18 is typical. It is neither very good nor very bad. It should be noted that the temperature directly under electrode 3 was 67C, whereas the thermocouple in this location indicated 85.2C at the end of the heating period. Presumably there was an equalization of temperature in the period just after heating stopped, with heat flowing outward in all horizontal directions from under each electrode. If this is the case a few minutes should be allowed for temperature equalization in a food, after heating and before serving. Also, if in a practical arrangement the temperature of an electrode is observed in order to follow the heating of the food, an allowance must be made for the fact that the electrode will be considerably above the average temperature of the food.

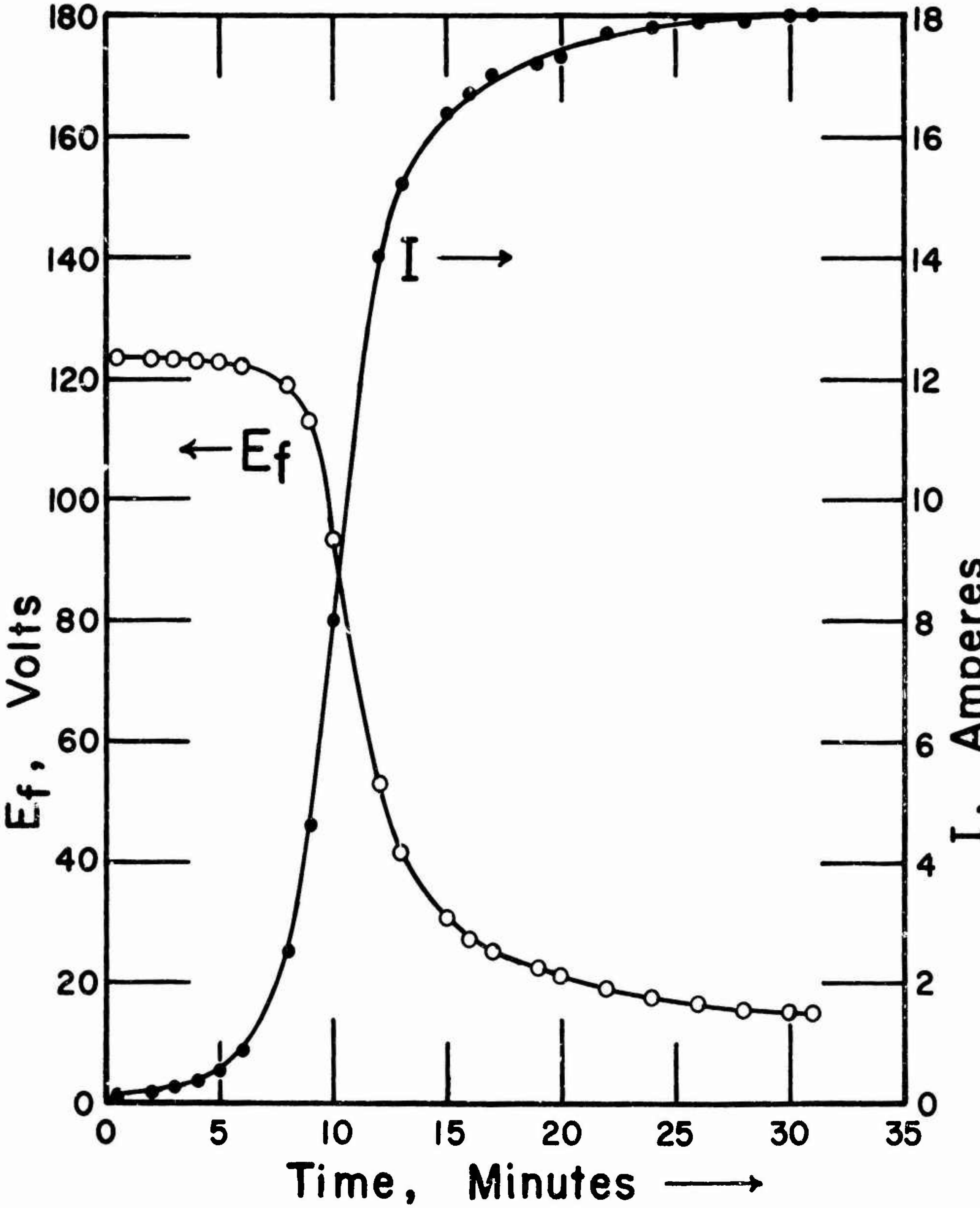

Figure 7. Variations of the voltage across the food and the current thru it during the course of Run 20.

The temperature distribution in the food at the end of Run 20 (Spanish rice) was investigated by probing the food with a stiff thermocouple. The temperature was much more uniform than in Run 18 (noodles and cheese). Whereas in Run 18 the 8 temperatures observed immediately under the 8 electrodes ranged from 49 to 73C, in Run 20 they ranged only from 74 to 80C. The spread in Run 18 was 24C; in Run 20, 6C. The temperatures found by probing at the specimen corners after Run 20 ranged from 43 to 57C. In Figure 4, points marked "average temperature" have been plotted. These show the average of all the temperatures found by probing, and the average time at which the probings were made.

5. Other Results

Figures 4, 5, and 7 and the discussion in Section 4 describe the more important findings of the present research to date. The data so far presented are supported by other runs, listed in Table 1, some made under conditions very similar to those described, and some made under poorer conditions before some of the most troublesome problems had been solved. Of the earlier results, only those which may have some permanent value will be described.

In all of the 20 runs listed in Table 1 the bottom electrode was a single metallic surface, almost always the bottom of a stainless-steel, half-size steam-table pan. In Runs 1, 2, and 3 the upper electrode was a single aluminum plate. After these three runs had shown that a single plate did not distribute the heating current adequately, an assembly consisting of 8 electrically-separate, square, flat-plate electrodes was constructed. Each electrode was 5.1 x 5.1 cm (2 x 2 inches) and was separated from its neighbors by 0.64 cm (0.25 inch). A current-splitter employing isolation transformers was constructed to supply 8 currents to the 8 electrodes, and although this splitter was used only once (in Run 4) the good results obtained pointed the way to the system subsequently adopted.

The first current-splitter employed isolation transformers having two primary windings. The two windings are intended to be put in parallel when the supply is 120 V and in series when the supply is 240 V. The series connection was used and the current entered the transformer at the midpoint, where the two windings were joined. It flowed in both directions from the point, approximately half of it leaving at each end of the primary. The secondaries of the transformers were not used. The first level of splitting was performed by a Triad Model N-67A isolation transformer, which had a capacity of 150 VA. The second level of splitting was performed by a pair of Triad Model N-68X isolation transformers of smaller size (50 VA). There was no third level of splitting as there is in Figure 1. The 8 electrodes and 8 lamps were connected as in Figure 1, but each of the 4 currents from the splitter supplied 2 lamps and 2 electrodes.

The isolation transformers served very satisfactorily as current splitters during the early part of the run but they were too small to be used at currents much above 1 ampere. So when the current reached its limit the transformers were simply bypassed so that the run could be completed at much higher currents. The entire run was satisfactory. Probably the use of a current splitter is more important in the early part of a run when the food is frozen than in the later part when the food is soft. The temperature uniformity at the end of Run 4 was good. This was probably due in part to the good distribution of current made by the splitter, and in part to the fact that the food was heated rather slowly.

After the advantages of good current-distribution had been demonstrated, it was obvious that larger transformers were needed, which would split a large total current (up to 18A) into 8 equal parts. At this point it was realized that ordinary autotransformers would do the job and the splitter shown in Figure 1 was quickly assembled.

The use of the 8 flat-plate electrodes was continued from Run 4 thru Run 10. In these runs trouble caused by poor contact between the food and one or more electrodes was often encountered and was mitigated by partially defeating the current-splitting function as previously described. The lateral separation between electrodes (0.64 cm, 0.25 inch) aggravated electrical breakdown problem, and when the apparatus in current use was constructed this distance was increased to 1.27 cm (0.5 inch).

Runs 3–7 were made on Creole squash. This food can be thawed and heated satisfactorily. As mentioned earlier, it lost large amounts of liquid when heated. Some plastic boxes are now being made up into which the food and the upper electrode assembly will fit snugly. The lower electrode will be a conducting sheet placed in the bottom of the box. It is expected that these boxes will prevent the loss of liquids when foods such as the squash are heated.

Runs 8–19 were made on noodles and cheese and one of the runs made on this material (Run 18) has already been described. In Run 8 great difficulty was experienced in obtaining electrical contact between the flat electrodes and the food. This was attributed to a top dressing of crumbs that had been sprinkled over the noodles and cheese. Most of the crumbs were removed from the specimens before Runs 9 and 10 were made and the trouble was much reduced.

In Run 11, one screw in each of the 8 electrodes was replaced by a screw carrying a sharp point that would penetrate into the food. It was thought that this might improve electrical contact between the electrodes and the food significantly. The energy distribution in this run was poor, but the sharp points did help the situation in the regions of the food that were close to them. Runs 12–20 were all made with the improved electrodes, each of which had 16 spikes.

Run 19, made on noodles and cheese, should be mentioned because it exhibited greater non-uniformity of temperature at the end of the run than any other experiment. Probing with the mercury thermometer showed temperatures directly beneath the electrodes ranging from 47 to 62C, which is not a large spread. The main (recorded) thermocouple in this run was directly under electrode 3. However, a second thermocouple was used in this run, located equidistant from the adjacent corners of electrodes 1, 2, 5, and 6 and near the midplane of the food in the vertical direction. This thermocouple indicated a temperature of only −3C at the end of the run. We thought the reading must be in error, but it was confirmed by the mercury thermometer, which gave a reading of 2C when placed near the couple. The mercury thermometer also indicated 2C at a point equidistant from the adjacent corners of electrodes 2, 3, 6 and 7 (center of the entire specimen).

It is possible that in Run 19 the initial heating was unusually fast, allowing less time than usual for lateral heat flow. This might generate a channel for electric current directly under each electrode which was not wiped out by the natural tendency of the electric current to spread and by the equalizing effect of heat flow.

The early work done on small specimens was very useful as a guide to what would be required in the later apparatus but does not add much to what has been discussed above. None of the electrodes used with the small specimens had sharp points. In the early experiments we did not explore the specimens for temperature uniformity and, since there was only one thermocouple in a specimen, a certain amount of non-uniformity could have gone undetected.

6. Discussion

There are 4 runs out of the 20 listed in Table 1 in which the food was heated to a recorded temperature of 73C (163 F) or above in 31 minutes or less and in which the temperature distribution was found to be "fair" or better. These are Runs 15, 17, and 18 on noodles and cheese and Run 20 on Spanish rice. The average energy supplied to the noodles and cheese was 0.128 kWh and that supplied to the Spanish rice was 0.174 kWH. There does not appear to be any problem in scaling up the experiment from a 22.9 x 11.4 cm (9 x 4.5 inches) area to a steam-table pan in which the food area is about 55.9 x 29.2 cm (22 x 11.5 inches), an area ratio of 5.4. The energy requirement of a full pan of Spanish rice, the food that has the higher heat requirement, is 0.174 x 5.4 = 0.940 kWh which will be rounded off upward to 1 kWh. The voltage across the food remains unchanged; the current and power each increase by the factor 5.4.

To obtain 1 kWh in 20 minutes, the time specified in Air Force Requirement 5–1, will require a power of 3 kW to be drawn from the line. This does not include any allowance for power that may be wasted in the control circuits. If reactive rather than resistive controls are used, the wasted power should be small compared to that developed

in the food. With 240 volts and 20 amperes available from the line, up to 4.8 kW can be taken from it, and so, as far as power is concerned, the heating time could be reduced to somewhat less than 20 minutes, in the case of Spanish rice at least.

However, the large resistance change of foods makes it difficult to keep the power near its maximum level at all times during the heating period. Referring to Figure 5, we see that the initial resistance of a 22.9 x 11.4 cm frozen food specimen is of the order of 1000 ohms and would be even higher at −23C (−10 F) which is the initial temperature specified. As the food is heated, the resistance rapidly falls. At the knees of the resistance curves, where melting is taking place, the resistance is of the order of 3 ohms; at the end of the run it is near 1 ohm.

It is of interest to see what must be done to keep the power developed in the food at a more nearly constant level than is possible with our present equipment. Also it will be helpful to scale up the data for a representative run so that it will apply to a full-size steam-table pan of food. Run 20 (Spanish rice) has been selected for this purpose; in Table 2 the experimental data for this run are given in full. In addition, the last three columns of this table contain the scaled-up data. In the scaling-up, the voltage across the specimen is assumed to remain unchanged, the current and the power increase by the scale factor (5.4) and the resistance is divided by this factor.

It is clear from Table 2 and from Figure 7 that in order to reduce heating times we must increase the power input on both sides of the maximum. This will require the use in the early part of the run of higher voltages than were available and in the later part of the run of higher currents than were available. It is of interest to consider an ideal situation in which a power of 4.8 kW is developed in a resistance R, the voltage and current being permitted to take on whatever values are necessary as R varies. Such a system could be realized with an ideal continuously variable transformer of sufficiently high capacity, supplied by a 240 V, 20 A line. Since power $P = E^2/R = I^2R$, a line of constant power on a log-log plot of E versus R is a straight line. The same is true of a similar plot of I versus R.

Figure 8 shows two such straight lines which give E and I respectively for P = 4.8 kW. Ignoring all considerations such as safety, the possibility of electrical breakdown, and the availability of practical devices for varying the voltage and current of the power used, but accepting a maximum power limit of 4.8 kW, Figure 8 tells us that for the scaled-up run of Table 2 we should at the beginning (R = 163 ohms) have E = 884 V and I = 5.4 A. At the "peak", which was found by interpolation, R = 1.28 ohms; here we should have E = 78 V and I = 61 A; at the end (R = 0.155 ohms) we should have E = 27 V and I = 176 A. If these conditions were realizable and the power of 4.8 kW were maintained continuously, the energy of 0.94 kWh required in the scaled-up run could be supplied in 12 minutes rather than in the 31 minutes of Table 2. Clearly the values

Table 2. Data on the power developed in Run 20, and the corresponding scaled-up values (x5.4) for a full-size steam-table pan of the same food.

TIME	E	ACTUAL			SCALED-UP		
		I	R	P	I	R	P
min	volts	amps	ohms	watts	amps	ohms	watts
0.5	123.2	0.14	880	17.2	0.76	163	92.9
2	123.2	.19	648	23.4	1.02	120	126
3	123.0	.26	473	32.0	1.40	87.5	173
4	122.9	.36	341	44.2	1.94	63.1	239
5	122.6	.53	231	65.0	2.86	42.8	351
6	122.0	.83	147	101	4.48	27.2	545
8	118.7	2.50	47.5	297	13.5	8.80	1604
9	112.8	4.60	24.5	519	24.8	4.54	2803
10	93.4	8.00	11.7	747	43.2	2.17	4034
12	52.7	14.0	3.76	738	75.6	0.696	3985
13	41.6	15.2	2.74	632	82.1	.507	3413
15	30.5	16.4	1.86	500	88.6	.344	2700
16	27.2	16.7	1.63	454	90.2	.301	2452
17	25.2	17.0	1.48	428	91.8	.274	2311
19	22.2	17.2	1.29	382	92.9	.239	2063
20	21.1	17.3	1.22	365	93.4	.226	1971
22	19.1	17.7	1.08	338	95.9	.200	1825
24	17.53	17.8	0.985	312	96.1	.182	1685
26	16.51	17.9	.922	296	96.7	.171	1598
28	15.71	17.9	.878	281	96.7	.163	1517
30	15.26	18.0	.848	275	97.2	.157	1485
31	15.09	18.0	.838	272	97.2	.155	1469

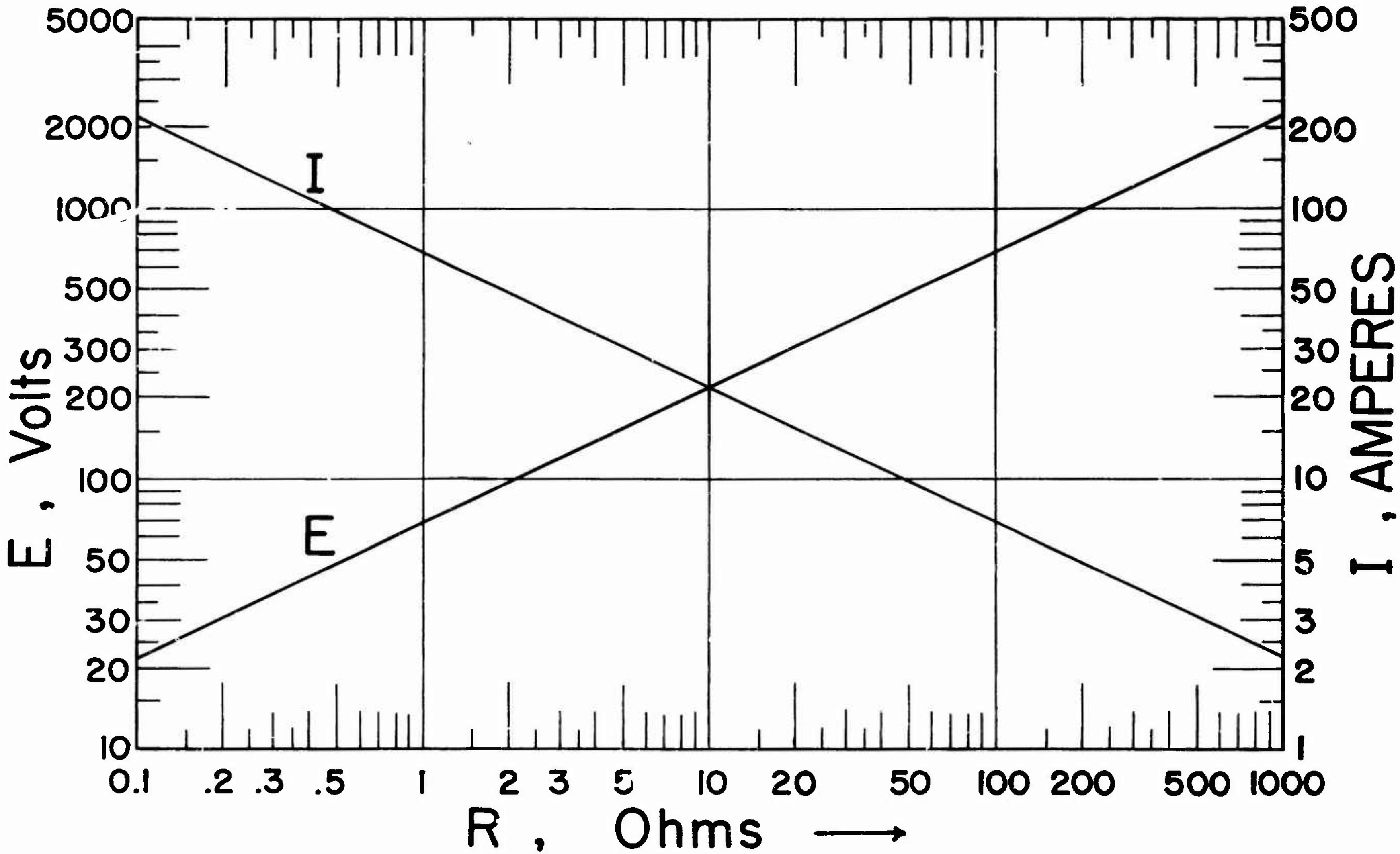

Figure 8. Log-log graph showing current and voltage required to develop 4.8 kW in a resistance of arbitrary size. When the supply line can deliver this amount of power at some fixed voltage, control equipment is required to change E (and hence I) appropriately as the resistance of the food changes.

of E and I shown in Figure 8 represent an ideal situation that can be approached but not fully realized in a practical equipment.

Taking one step in the direction of the practical we note that a voltage of 884 is too high for convenient and safe use. A 240 V autotransformer wired for the usual overvoltage delivers up to 270 V, which we will accept as safe for use if reasonable precautions are taken. An increase to this voltage would raise the heating rate in the early part of the scaled-up run by a factor of $(270/123.2)^2 = 4.80$. This increased rate could be maintained until the power limit given by Figure 8 was reached.

If an autotransformer delivering 0 to 270 V were used in connection with two or more stepdown transformers, with ratios of, say, 1:1, 1:2, and 1:4, substantial improvements in power delivery over the present system could be made. A system employing only two transformers would be less effective, but better than anything used so far. A calculation for a system using two transformers (1:1 and 1:4) indicated that heating times of 20 minutes or less could be achieved. The 1:1 transformer should be used for the first 35% of the heating time and the 1:4 transformer for the remainder.

There are many relatively simple solid-state devices for controlling electric power. None of these have been tried out in the present research but they offer possibilities that should be investigated after the feasibility of rapid ohmic heating has been more fully demonstrated.

7. Conclusions and Recommendations

Air Force Requirement 5–1 can be met by the method of direct ohmic heating. The requirement has not yet been met in all respects in any single experiment, but there is every reason to believe that it can be met. One point yet to be investigated is the initial heating rate when the starting temperature is −23C (−10 F). So far the lowest starting temperature is −16C. Some other points that require further study have been mentioned in the introduction and in the body of the paper.

Perhaps the most important task remaining is to investigate a larger number of foods, especially meat and stew dishes that might be served as entrees. Another type of information that would be very helpful in rapid-heating experiments and applications is data on specific heats and enthalpies of the foods most often to be heated. Such information could be obtained with the water calorimeter recently constructed, which was mentioned earlier. It seems likely that the specific heats of foods depend strongly on their water content and it would be useful to correlate specific heat with water content. Enthalpy changes tell us how much electrical energy will be required.

Another property of foods that it would be desirable to know is electrical resistivity. The little information gathered so far indicates that resistivity may not vary greatly from

food to food. If foods of extremely high or extremely low resistivity, relative to the average, are found, they will probably give trouble in direct ohmic heating.

There are many practical matters that should be investigated if ohmic heating is accepted as the solution of the rapid-heating problem. As examples: Can the food temperature be found from the electrode temperature, and if so should a thermocouple, resistor, or thermistor be used? Should auxiliary heat be generated in the upper electrodes? Can the points on the upper electrodes be made fewer and more blunt? This would be advantageous, as the holes left by the spikes may detract from the appearance of the food in some cases. How can the operator be sure he has uniform heating? What is the best way to control the electric power?

Rather than extend the above list of details, it would be better to consolidate the progress made so far and actually heat the foods discussed, plus several additional foods, in the specified times. When this has been done another full-scale critical evaluation of the status of the problem should be made.